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THE AMBIENT AND PERTURBED SOLAR WIND: FROM THE SUN TO 1 AU

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SUMMARY

The overall objective of the proposed research was to use numerical solutions of the magnetohydrodynamic (MHD) equations along with comparisons of the computed results with observations to study the following topics: (1) ambient solar wind solutions that extend from the solar surface to 1 astronomical unit (AU), contain closed magnetic structures near the Sun, and are consistent with observed values; (2) magnetic and plasma structures in coronal mass ejections (CMEs) as they propagate to the interplanetary medium; (3) relation of MHD shocks to CMEs in the interplanetary medium; (4) interaction of MHD shocks with structures (such as other shocks, corotating interaction regions, current sheets) in the interplanetary plasma; and (5) simulations of observed interplanetary structures. A planned close collaboration with data analysts served to make the model more relevant to the data. The outcome of this research program is an improved understanding of the physical processes occurring in solar-generated disturbances in the interplanetary medium between the Sun and 1 AU.

PUBLICATIONS

Two separate papers reporting the research performed with support from this grant are in preparation.

SUMMARY OF RESEARCH

During the first year of the proposed investigation, MHD codes developed by the PI were used to generate solutions for the ambient solar wind that contain closed magnetic structures (coronal streamers) near the surface of the Sun and for which the computed values of physical quantities are consistent with available observations from the Sun to 1 AU. Driving mechanisms (e.g., magnetic flux emergence, photospheric shear) at the coronal base of the closed magnetic stuctures were then used to generate CMEs, and their evolution was followed numerically through the interplanetary medium. Specific studies completed during the first year include shock-shock interactions, shock conversions, and initiation of an effort to determine the three-dimensional configurations of CMEs as they propagate to the interplanetary medium.

Additional necessary physics were then incorporated into the solar wind model. This topic covers the inclusion and evaluation of the physics needed to generate a physically consistent ambient solar wind and interplanetary disturbance. It is a nontrivial problem to represent the initial solar wind and the driver mechanisms realistically and requires more than just developing basic 2-D and 3-D MHD codes, which are already available for this study. A large part of the work on this task involved using the numerical relaxation procedure to find ambient solar wind solutions, for selected models of the thermodynamics, that are consistent with available observations from near the Sun to 1 AU. The initial magnetic field configuration was also computed self-consistently as part of this work. A large portion of this work was completed with 2-D models since this part of the effort serves mainly as a test bed for the geometrically more appropriate (and CPU-intensive) 3-D studies. One of the primary results of this study was to demonstrate that a realistic ambient solar wind can only be generated within the confines of this fluid model if either the temperature or the polytropic index are certain specified functions of radial distance. The temperature must decrease with radius and the polytropic index must be near one near the Sun and increase to approximately 5/3 near 1 AU. When either the temperature or the polytropic function are given as a function of radius, the other quantity is determined from the relaxation procedure used to compute the ambient solar wind. Observed ambient solar wind variations with latitude can also be mimicked with given temperature or polytropic index variations. Although this may seem to be a fairly arbitrary procedure, the necessity for this procedure perhaps says something about the fundamental physics of the solar wind or may demonstrate a basic limitation in a single-fluid model.

Once the ambient solar wind has been determined in 2-D and 3-D models, the next step involved development of multi-dimensional MHD simulations of interplanetary disturbances. This simulation study offers the opportunity to make real progress toward a more complete understanding of the solar/interplanetary connection. For instance, although MHD shocks are an important part of most interplanetary disturbances (CMEs) generated by dynamic events near the solar surface, the relation of the shock to the driver mechanism remains, for the most part, unclear, other than the fact that the shock wave (if one is formed) would be expected to precede the interplanetary signature of the driver. In earlier work I studied in detail the relation of shocks to CMEs observed by coronagraphs in the near-Sun corona and found that only near the center of the CME does shock compression contribute to the observed image. The shocks at the flanks of the CME are often too weak for the density compression to be observed in coronagraphs. The interplanetary consequences of such composite CME (the bright image identified in coronagraphs) and shock structures had yet to be determined.

Both 2-D and 3-D simulations were used to study the evolution of solar eruptions as they propagated out into the solar wind near the Earth's orbit. The primary factors that determine the signature of a solar eruption near 1 AU are the initial magnetic structure in which the eruption occurs and the nature of the driving mechanism. For instance, simulations have shown for years that the essentially instantaneous release of a large amount of energy near the solar surface in an essentially open magnetic field will result is a coronal structure that expands in all directions with a strong shock at the leading edge. There is not a whole lot of observational evidence to support that the majority of solar eruptions occur in this manner. The hypothesis that solar eruptions occur as a result of the build-up of stressed magnetic fields in a closed magnetic structure and the release of that energy when the magnetic field can no longer be contained near the Sun and expand outward. Indeed, the present simulations have demonstrated the significant difference in the eruption signature near 1 AU when the driver is more consistent with observations. The coronal disturbance produced by the more realistic driver mechanism is also more in agreement with observations taken near 1 AU. The actual thermodynamic conditions and velocity of the ambient solar wind have only a secondary effect of the coronal disturbance near 1 AU. The magnetic structure and the driver mechanism near the Sun are the most important factors.

Other work that required 3-D MHD codes was also initiated, but using less sophisticated drivers than magnetic drivers, that involved the study of the interaction of structures in the solar wind, e.g., the interaction of MHD shocks with corotating interaction regions and with current sheets. Moreover, despite the emphasis in this work on 3-D simulations, one of the studies where the essential physics could be studied in 2-D involved investigations of the interaction of MHD shocks and the possible conversion of MHD shocks from one type to another. With respect to this latter topic, the concave upward shape or the CME leading edge seen in coronagraphs suggests that either slow or intermediate MHD shocks form within about 6 R_s of the solar surface, as demonstrated in a series of papers by Steinolfson and Hundhausen. Yet reported observations of either slow or intermediate shocks in the interplanetary medium are relatively rare. The obvious question, then, involves the possible conversion of these shocks to fast shocks as they move from the low-beta corona near the Sun to the higher-beta interplanetary medium. The present study has shown the due to the changing magnetic structure in the ambient solar wind, both slow and intermediate shocks formed near the Sun are converted to fast shocks near 1 AU. Only under very limited conditions (primarily a radial ambient magnetic field) will the slow and intermediate shocks survive out to 1 AU.